LCA Case Studies

Life Cycle Assessment of Water Production Technologies

Part 1: Life Cycle Assessment of Different Commercial Desalination Technologies (MSF, MED, RO)

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Preamble. This series of two papers analyses and compares the environmental loads of different water production technologies in order to establish, in a global, rigorous and objective way, the less aggressive technology for the environment with the present state of the art of the technology. Further, it is also presented an estimation of the potential environmental loads that the considered technologies could provoke in future, taking into account the most suitable evolution of the technology. **Part 1** presents the assessment of most commercial desalination technologies which are spread worldwide: Reverse Osmosis, Multi Effect Desalination and Multi Stage Flash. **Part 2** presents the comparative LCA analysis of a big hydraulic infrastructure, as is to be found in the Ebro River Water Transfer project, with respect to desalination.

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Abstract

Intention, Goal and Background. In this paper, some relevant results of a research work are presented, the main aim of which consists of performing the environmental assessment of different water production technologies in order to establish, in a global, rigorous and objective way, the less aggressive technology for the environment of potable water supply to the end users. That is, the scope of this paper is mostly oriented to the comparative Life Cycle Assessment of different water production technologies instead of presenting new advancements in the LCA methodology. In Part 1, the environmental loads associated with the most widespread and important commercial desalination technologies all over the world - Reverse Osmosis (RO), Multi Effect Desalination (MED) and Multi Stage Flash (MSF) – are compared. The assessment technique is the Life Cycle Analysis (LCA), which includes the entire life cycle of each technology, encompassing: extraction and processing raw materials, manufacturing, transportation and distribution, operation and final waste disposal.-

Methods and Main Features. The software SimaPro 5.0, developed by Dutch PRé Consultants, has been used as the analysis tool, because it is a well known, internationally accepted and validated tool. Different evaluation methods have been applied in the LCA evaluation: CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99. Data used in the inventory analysis of this Part 1 come from: a) existing plants in operation; b) data bases implemented in the SimaPro 5.0 software -BUWAL 250, ETH-ESU 96, IDEMAT 2001.
Different scenarios have been analyzed in both parts in order to estimate, not only the potential of reduction of the provoked environmental loads with the present state of the art of technology, but also the most likely future trend of technological evolution. In Part 1, different energy production models and the integration of desalination with other productive processes are studied, while the effect of the most likely technological evolution in the mid-term, and the estimation of the environmental loads to the water transfer during drought periods are considered in Part 2.

Results and Discussion. The main contribution to the global environmental impact of desalination technologies comes from the operation, while the other phases, construction and disposal, are almost negligible when compared to it. Energy is very important in desalination, for this reason the environmental loads change a lot depending on the technology used for providing the energy used in the desalination process. Among the different analyzed technologies, RO is the least aggressive desalination technology (one order of magnitude lower than the thermal processes, MSF and MED) for the environment. When integrating thermal desalination with other productive processes taking advantage of the residual heat, the environmental loads of thermal desalination technologies is highly reduced, obtaining similar loads to that of RO. The environmental loads of desalination technologies are significantly reduced when an energy model based on renewable energies is used. Taking into account the technological evolution, which is experiencing the RO, a reduction of its environmental load by about 40% is to be expected in the mid-term.

Conclusion. The main conclusion of Part 1 is that, with the present state of the art of the technology, RO is clearly the desalination technology with a reduced environmental load (one order of magnitude lower than the thermal processes, MSF and MED). In the case of thermal desalination technologies, their environmental load can be highly reduced (about 1,000 times less) when integrated with other industrial processes. In the case of RO, the scores and the airborne emissions obtained from an electricity production model based on renewable energies are about 65-70 times lower than those obtained when the electricity production model is mainly based on fossil fuels.

Recommendations and Outlook. Although desalination technologies are energy intensive and provoke an important environmental load, they present a high potential in being reduced since: a) in the mid-term, it is to be expected that the different technologies could improve their efficiency significantly, b) the environmental loads would be highly reduced if the energy production models were not mainly based on fossil fuels and c) the energy consumption, particularly in the case of thermal desalination, can be drastically reduced when integrating desalination with other productive processes. The results presented in this paper indicate that a very interesting and promising field of research is available in order to reduce the environmental load of these vigorous and increasing desalination technologies.

Keywords: Comparative life cycle assessment; desalination; multiple effect distillation (MED); multiple stage flash (MSF); reverse osmosis (RO)

1 Introduction

One of the most important, increasing problems nowadays, which is becoming more and more acute, is the scarcity of fresh water with enough quality for human consumption, and industrial and agricultural use. The increasing world population growth, together with the increasing industrial and agricultural activities all over the world, are provoking the depletion and pollution of fresh water resources. Hence, although the total stock of water on the Earth remains constant, the fresh water supply is becoming more and more scarce. Moreover, water issues encompass very complex and multidisciplinary problems, that are provoking debates and serious conflicts in many regions of the world, particularly when dealing with the distribution and reliable supply in areas suffering from water stress. It is estimated that 1,700 m^3 per capita is the annual amount of water required for an adequate fresh water supply without compromising the environment requirements, and 1,000 m^3/year per capita is the water stress benchmark level. Water stress and water scarcity represent a very important problem in many regions of the planet. About 20% of the world population – more than 1.2 billion people – is lacking potable water with a minimum of sanitation conditions. 80% of all known diseases are related to water misuse, and it is estimated that in 2025 about 2/3 of the world population will suffer from water stress [1]. All the previous data show that the fresh water scarcity is a problem of paramount importance, and the provision of fresh water for 6 billion people in the world in a sustainable way is one of the most important problems that humanity should envisage during the XXI century.

Seawater can be desalted and supplied in large quantity, and with a very high quality. Unfortunately, this requires a great amount of energy, and the overwhelming majority of the energy currently used for desalination is obtained from fossil fuels. In spite of that, desalination, which is of a continuously increasing importance, is already a means of augmenting fresh water resources in many parts of the world, including the European Union and particularly in the Mediterranean countries [2]. In 2002, just over 30 million cubic meters of fresh water were being produced per day all over the world, with 18 Mm^3/d desalted from seawater [3]. That represents a 30-fold increase in global capacity over three decades.

Even though desalination is a mature technology with increasing importance and exponential expansion, its environmental impact is not well known yet. More and more sustainability assessment [4] and environmental studies related with desalination technologies are being conducted [5]; most of them concerned with brine disposal and local problems [6–8].

Taking into account these aspects and the dimension of the problem of fresh water supply, it is essential to know the water production technologies that provoke a lower environmental impact with a global and broad perspective. In this context, this paper presents some relevant results of a research work, partially funded by the Spanish Ministry of Science and Technology (Project REN 2001-0292) and the Government of Aragón, whose main aim consists in performing the environmental assessment of different water production technologies in order to establish a less aggressive technology for the environment in a rigorous and objective way. The environmental assessment method applied is Life Cycle Assessment (LCA), which is one of the most powerful and internationally accepted tools being used to examine the environmental cradle-to-grave consequences of making and using products and services by identifying and quantifying energy, material usage and waste discharges. The ISO 14040 general impact categories, which are internationally accepted as standard indicators for environmental impact assessment, have been evaluated, and different evaluation methods (CML 2 Baseline 2000, Eco-Points 97 and Eco-Indicator 99) have been considered.

Part 1 of the paper analyzes and compares the most important commercial desalination technologies, encompassing more than 90% of desalinated water in the world: multistage flash (MSF), multi-effect evaporation (MED) and reverse osmosis (RO), providing a good idea of the technology that provokes a lower global impact and the most important factors that should be taken into account for decreasing the environmental loads associated with desalination.

In Part 2, the difficult task of comparing a conventional hydraulic project is envisaged, which is the case of the Ebro River Water Transfer project proposed in the Spanish National Hydrologic Plan, with the desalination technology. It is important to remark that this analysis provides an interesting general and global, 'cradle to the grave' outlook of the environmental loads provoked by a specific big hydraulic infrastructure as compared to one of the feasible alternatives: desalination technology.

In both cases, the assessment includes the entire life cycle of each desalination process encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, plant operation and final waste disposal.

2 Desalination Technologies

The desalination technologies consist of reducing the saline concentration of water to convert it into suitable water to be consumed by humans. Its source is inexhaustible if we talk about seawater desalination, but we can also consider the use of brackish water from aquifers. Conventional desalination technologies produce more than 90% of desalted water in the world and they can be sorted into two great groups or processes: thermal and membrane separation.

2.1 Thermal desalting

The most ancient ways of desalting seawater or brackish water are based on distillation processes and involve some form of boiling or evaporation. The required thermal energy is produced in steam generators, waste heat boilers or through the extraction of backpressure steam from the turbines in power stations. The most important thermal desalination processes are Multiple Effect Distillation (MED) and Multi Stage Flash (MSF) [9].

2.1.1 Multiple effect distillation (MED)

In a simple stage, seawater can be boiled releasing steam which, when condensed, produces pure water. Many effects can be connected together to make the process more efficient. To achieve this, each stage, or effect, must be operated at different pressures. In an MED plant [9] (**Fig. 1**), seawater enters the first stage and is raised to the boiling point after being preheated in tubes. The seawater is either sprayed or otherwise distributed onto the surface of evaporator tubes in a thin film to promote rapid boiling and evaporation. The tubes are heated by steam from a boiler, or from another source, which is condensed on the opposite side of the tubes. The condensate from the boiler steam is recycled to the boiler for reuse. Only a portion of the seawater applied to the tubes in the first stage is evaporated. The remaining water is fed to the second stage, where it is again applied to a tube bundle. These tubes are, in turn, heated by the vapor created in the first stage. This vapor is condensed to produce fresh water, while giving up heat to evaporate a portion of the remaining seawater feed for the next effect. This continues for several stages, with 8 or 16 effects being carried out in a typical large plant.

2.1.2 Multi stage flash desalination (MSF)

If the water is heated to 100ºC, but held under pressure until it is released into a vacuum chamber, the water flashes into steam. Connecting multiple stages at successively lower pressures is the principle behind MSF (**Fig. 2**). In this process, evaporation and condensation is split into many stages, thereby increasing efficiency [10]. Incoming seawater is passed through heat exchanger tubes, where the water vapor (on the outside of tubes) condenses at progressively higher temperatures. Finally, it is passed to a heater where steam from an external source supplies the energy for the process and heats the seawater to the maximum process temperature. The seawater then passes to the evaporator vessel where pressure is decreased, causing it to boil or flash. This process is repeated in many stages, the pressure being reduced so that flashing occurs at progressively lower temperatures. The condensed vapor is distilled water.

2.2 Reverse osmosis membrane separation

Semipermeable and ion-specific membranes can also be used to desalt seawater. The membrane process is based on separation rather than distillation (although membrane distillation can also be performed). Reverse osmosis membranes basically let water pass through them, but reject the passage of salt ions, in fact, a small percentage, that is 0.4% for new membranes of sea water salts, passes or leaks around seals. For potable water and agricultural use, and mostly for industrial applications, this leakage is acceptable. The operational pressure of reverse osmosis systems is a function of the feed water salinity [11]. Membrane processes usually are driven by electric pumps. A typical RO plant is depicted

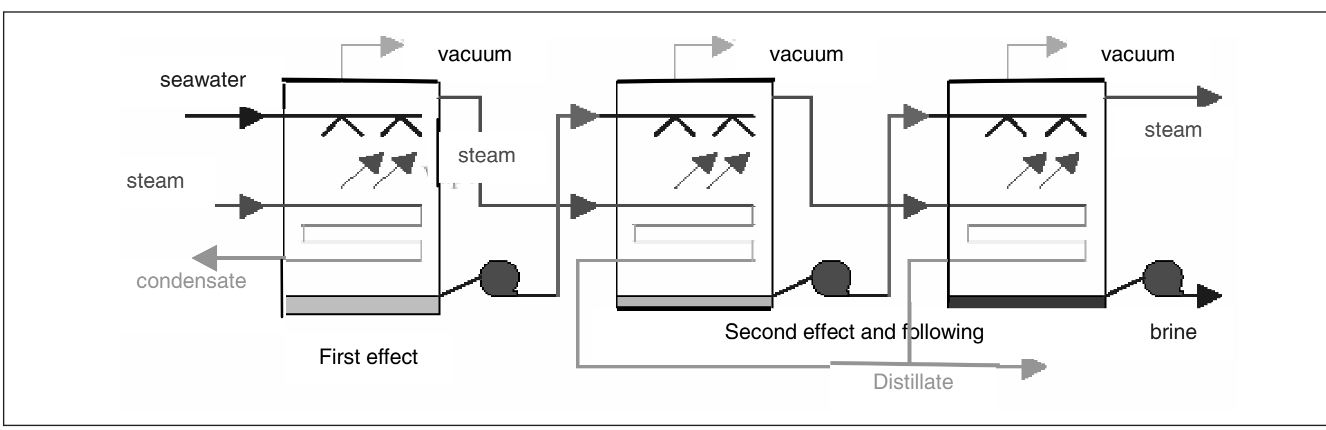

Fig. 1: MED process diagram

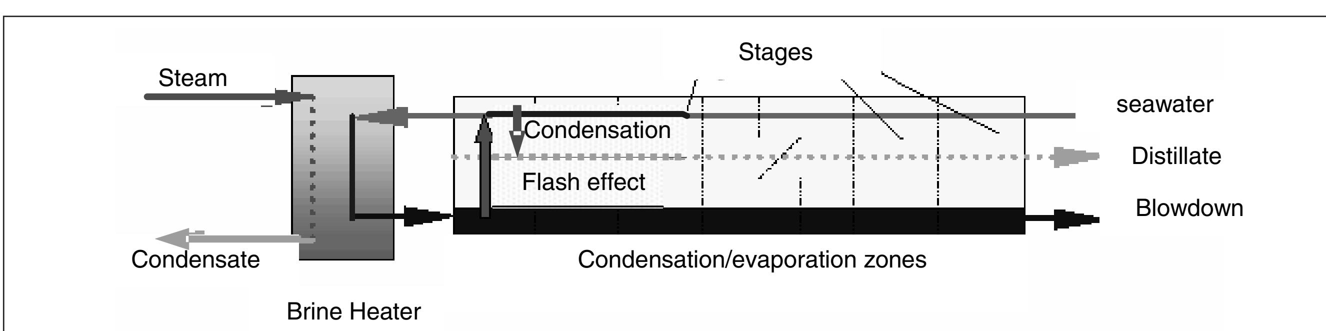

Fig. 2: MSF process diagram

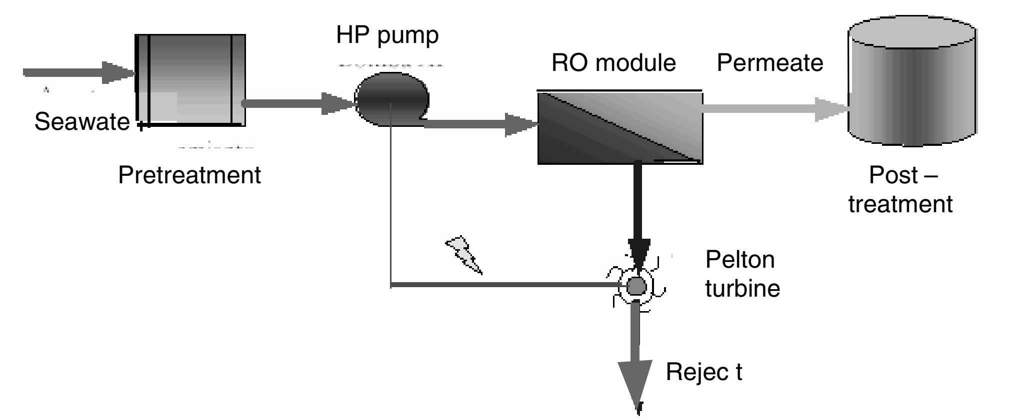

Fig. 3: Typical RO plant layout

in **Fig. 3**. The seawater passing through the modules is not completely desalted: a part is rejected as brine. The mechanical energy which is used in energy recovery systems [12], before returning this brine to the sea, permits one to achieve a significant energy saving.

3 LCA Methodology

The analysis presented in this paper is mostly oriented to the comparative Life Cycle Assessment of different water production technologies, instead of presenting new advancements in the LCA methodology. For this reason, the selected assessment tool is SimPro 5.0, which is a well known, internationally accepted and validated software.

SimaPro 5.0 is the fifth generation of a program developed by Dutch PRé Consultants in 1989 [13]. The results are presented in scores or graphs, varying from a list of substances (inputs and outputs), characterized scores, normalized scores or evaluated scores. The program contains environmental data [14–16] collected in Europe by several well-known companies, which are reported and publicly available. SimaPro 5.0 also contains several methods based on European or world figures to evaluate the outcomes of the inventory stage of an LCA (the lists of substances) [17]. As a consequence, different results can be obtained depending on the evaluation method applied. Depending on the different criteria applied for evaluating the importance of the different environmental loads and/or damages, different valuation for the global LCA can be obtained. Thus, in order to obtain as much of an objective, rigorous and complete outlook of the environmental damage of the technologies as possible, different criteria for evaluating the importance of their corresponding environmental impacts have been applied in this work: CML 2 baseline 2000, Eco-Indicator 99 (EI 99) and Ecopoints 97. The CML 2 baseline 2000 and EI 99 are chosen because they are new extended versions of their predecessors: CML 1992 and Eco-Indicator 95, respectively.

The CML method (Centre for Environmental Science, Leiden University, the Netherlands) elaborates the problem-oriented (midpoint) approach [17]. For impact categories a baseline indicator (category indicators at midpoint-level) is selected, based on the principle of the best available practice. This method consists of Classification, Characterization and Normalization stages for the LCIA.

The Ecopoints 97 method, developed by WUBAL (Bundesamt fur Umwelt und Landschaft – Swiss Environmental Agency, Bern, Switzerland), is based on the distance-to-target principle; the targets are set by national policies (of the Netherlands and Switzerland) [17]. The distance between the current level of an impact and the target level is assumed to be representative of the seriousness of emissions. This method consists of Classification, Characterization, Normalization and Valuation stages.

A panel of experts and non-experts elaborated the EI 99. It uses the damage-oriented (endpoint) approach and several weighting factors to normalize the scores and to evaluate the different environmental issues [18]. The damage assessment step has been implemented: the impact category indicator results that are calculated in the Characterization step have the same unit and are added to form damage categories. The damage categories are normalized to a European level (damage caused by one European inhabitant per year), based on 1993, including some updates for the most important emissions.

The EPS 2000 and EDIP/UMIP 96 methodologies are also included in the SimaPro 5.0 software (oriented for product and process design), and have not been considered in this work because they were out of the scope of our study.

3.2 Impact assessment

The impact categories with a weight of less 1% of the global impact have been neglected. For MSF, for example, Land Use and Radiation (impact categories of EI 99) have 0.47% and 0.05% of the global impact, respectively; Human toxicity and Eutrophication (impact categories of CML *baseline*) have 0.33% and 0.27% respectively; and Metals (soil) and Ozone layer (impact categories of Ecopoints 97) have 0.035% and 0.03% of the global impact, respectively. The different selected impact categories used by the three evaluation methods are shown in **Table 1**. The assessment process can be divided in the next steps [19–21]:

- Classification and characterization
- Normalization
- Evaluation

Table 1: Impact categories included in the chosen evaluation methods

CML 2 *baseline*	Ecopoints 97	EI 99
Abiotic depletion	NOx	Carcinogens
Global warming	SOx	Respiratory Inorganic
Marine aquatic eco-toxicity	NMVOC [a]	Climate change
Acidification	CO_2	Ecotoxicity
	Waste	Acidification / Eutrophication
	Energy	Fossil fuels

[a] Non-Methane Volatile Organic Compound

In each step, the inventory data are manipulated successively, as a consequence, decreasing in amount or complication, and consequently providing its interpretation. But this process has a cost: inventory data are objective (within their margins of error), but each new interpreted element incorporates a certain subjectivity associated with the model used, so we can find only one number or environmental rate describing the system (evaluation step) at the end of the interpretation process, which is very easy to understand, but very subjective. For this reason, different impact assessments have been applied in order to obtain as many rigorous conclusions as possible.

3.3 Description of the analyzed systems

The considered MSF seawater desalination plant is a brine recirculation flow type, and has a high temperature, anti-scale treatment and cross-tube configuration. It has a unit or evaporator formed by 20 stages, which produces on average of 45,500 m^3/day of desalted water. The thermal energy consumed by the plant to produce 1 m^3 of desalted water is about 333 MJ, produced in a boiler fueled with natural gas, and the mechanical energy consumption is 4 kWh/m^3. The construction and material data have been adapted from real MSF desalination plants (further details can be found in [22–26]).

The analyzed MED seawater desalination plant has a Horizontal Falling Film (HFF) tube exchanger. It has five units formed by 14 stages; the whole plant produces about 45,000 m^3/day of desalted water. The thermal energy consumed, produced in a boiler fueled with natural gas, is about 263 MJ/ per m^3 of desalted water produced, and the mechanical energy consumption is 2 kWh/m^3. The material quantities have been extrapolated from MSF real desalination plants due to a lack of reliable, real data (see [22–26] for further details).

The studied RO seawater desalination plant consists of 8 trains, with a total capacity of 46,000 m^3/day. Each train consists of 82 pressure tubes and each tube has 7 spirally-wound reverse osmosis membranes (model SU-820 FA), with an average life of 5 years [27–29]. The mechanical energy consumption is 4 kWh/m^3. Data have been adapted from real RO desalination plants [22,27–29].

The considered functional unit for the LCA analysis is the production of 45,500 m^3/day of potable water, with 8,000 hours of operation per year, that is, about 15 hm^3/year. The desalination plants have an average lifetime of 25 years, and it has been considered that the membranes in the RO plant are replaced every 5 years, which is a conservative assumption. Membrane replacement highly depends on the salinity and properties of seawater to be desalted. In the Mediterranean, for instance, the membrane replacement period (7–8 years) is longer than in the Gulf region, where the salinity of seawater is higher and replacement periods are significantly shortened as a consequence [12,27]. The system boundaries for a desalination plant are: desalination plant components, installation construction materials and their transformation processes, operation and maintenance phases, and, finally, the disassembly at the end of its useful life.

The assumptions and limitations that have not been considered in the process definitions are:

- The desalted water quality satisfactorily obeys the legal minimum requirements established by 98/83/CEE European Directive as being qualified for human consumption. For this reason, the quality of desalted water is not analyzed, although the water quality obtained by RO is lower with respect to the water produced by distillation.
- The effects of brine disposal from desalination plants on marine fauna and flora have not been considered due to the lack of reliable data. Anyway, according to several studies recently conducted [6–8,30], it seems that brine impacts are not very important and can be minimized, but this is an issue that should be studied carefully and rigorously.
- The disposal of consumed chemical additives (coagulants, anti-scalants…) has been neglected, because their volumes are very small.
- In respect to energy, data from the UCPTE European electricity (database BUWAL 250) [15] and natural gas from Europe (database ETH-ESU 96) [16] have been chosen as inputs. Primary sources of the European electricity production system are, on average: 43% thermal origin, 40% nuclear origin and 17% hydropower origin; including the production of primary energy, the processing and transport of the primary sources (fuel, lignite, gas, hydropower and nuclear power) and energy losses (efficiency of 30%), and excluding the infrastructure of the energy systems. The natural gas system includes its production, delivery and combustion in boilers.
- Noise is not considered due to the relatively long distance of large desalination plants from inhabited towns and villages.

The cut-off criteria applied for the analysis are: system components whose economic value is lower than 1% of the total value of the system and life cycle phases whose contribution is less than 0.1% of the total environmental load.

4 Results

In this section, the LCA results of MSF, MED and RO desalination processes are compared. Moreover, the results corresponding to two different analyzed scenarios are also included in order to estimate the evolution of environmental loads when feasible technological changes would be achieved: MSF and MED processes driven by residual thermal energy and different production electricity models for all the systems.

The detailed inventory tables, including all input and output substances (raw material, airborne, water and soil emissions and waste) of all considered systems, are listed elsewhere [22].

4.1 LCA of MSF, MED and RO

Table 2 shows the most relevant airborne emissions produced by the analyzed desalination processes along their life cycle. In general, MSF is the technology most pollutanting the atmosphere; CO_2 and NO_x emissions of RO are one order of magnitude less than those corresponding to thermal processes (MSF and MED). The LCA results in percentage obtained for each life cycle phase of each technology and for different methods are shown in **Table 3**.

Note how the final disposal phase at the end of the life cycle is negligible and the assembly phase has a significantly lower environmental load than the operational phase in all systems and methods. This result confirms that desalination technologies are really energy intensive systems, and provides a quantification of the importance of energy in the environmental loads provoked by desalination. In other words, energy issues play a key role when reducing the environmental load associated with desalination, as it is shown in the scenarios presented in the next sections.

Table 3 shows the overall scores obtained with the three methods for each desalination technology. It can be observed how, of the three methods, the MSF and RO desalination plants have the highest and lowest environmental load, respectively. In **Fig. 4**, the scores are depicted which have been obtained for each impact category corresponding to each technology when applying the EI 99 method. The fossil fuel impact category causes the highest contribution to global impact. Similar results are obtained when applying Ecopoints 97 and CML 2 *baseline* methods [22]. The MED total score has the same order of magnitude as MSF, and RO scores are approximately one order of magnitude lower than those corresponding to thermal technologies.

Table 2: Relevant airborne emissions[a] produced by desalination systems

	MSF	MED	RO
kg. CO_2 /m^3 desalted water	23.41	18.05	1.78
g. dust /m^3 desalted water	2.04	1.02	2.07
g. NO_x /m^3 desalted water	28.29	21.41	3.87
g. NMVOC/m^3 des. water	7.90	5.85	1.10
g. SO_x /m^3 desalted water	27.92	26.49	10.68

[a] These airborne substances have been selected because a) they are the typical emissions associated with energy production systems, b) they are usually considered in the regulations of each country, c) they are updated, and d) their emitted quantities are higher than other emitted substances appearing in the Inventory Tables.

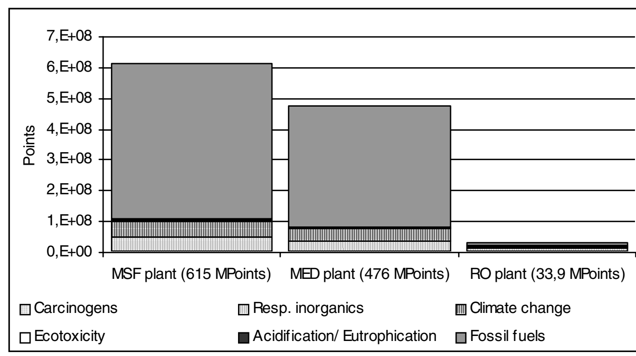

Fig. 4: EI 99 method, Hierarchist Perspective H/A, where Human Health and Ecosystem Quality Damages have been assigned 400 Points and Resources Damage has 200 Points. Overall scores obtained in the Evaluation phase for each desalination technology. The calculus bases are about 379 hm^3, 375 hm^3 and 383 hm^3 of total water production for MSF, MED and RO, respectively

Table 3: Environmental load depending on the assessment method corresponding to each life cycle phase and overall scores for the different desalination technologies. The calculus bases are about 379 hm^3, 375 hm^3 and 383 hm^3 of total water production for MSF, MED and RO, respectively

Process	Life cycle phase	Unit	EI 99	Ecopoints 97	CML 2 *baseline*
MSF	Assembly	%	0.78	3.69	1.31
	Operation	%	99.21	96.31	98.69
	Final disposal	%	0	0	0
Total scores			615 Mpoints	3,490 GPoints	0.0168
MED	Assembly	%	2.00	11.37	3.01
	Operation	%	98.00	88.63	96.99
	Final disposal	%	0	0	0
Total scores			476 Mpoints	2,790 GPoints	0.0116
RO	Assembly	%	1.53	1.55	0.88
	Membranes	%	0.91	0.36	0.08
	Operation	%	97.56	98.09	99.04
	Final disposal		0	0	0
Total scores			33.9 Mpoints	500 GPoints	0.0053

4.1.1 LCA of MSF, MED driven by residual thermal energy

The thermal desalination (MSF and MED) could also be driven by thermal energy at a lower temperature (about 100 ºC). This situation opens the possibility of taking advantage of waste heat coming from other industrial processes. In this way, very important energy saving can be achieved, because the consumption of any fuel could be avoided. **Table 4** shows the most relevant emissions produced when the thermal desalination processes are entirely driven by waste heat instead of fossil fuels. Comparing with the results presented in Table 3, the importance of energy in these technologies can clearly be shown. When thermal desalination plants are driven by waste heat, it produces a decrease of 77% for MSF emissions and 84% for MED emissions, on average. The values of dust in Table 4 remain the same as those appearing in Table 2 because this substance is associated to the assembly stage and to the coal required for producing the electricity consumed by the pumps, which are the same in both cases. Note that the heat (thermal energy) consumed for driving the thermal desalination plants analyzed in Table 2 is produced in a boiler fueled with natural gas, which does not emit dust.

Table 5 shows the overall score comparison for MSF and MED driven by waste heat and RO. Comparing **Table 5** with Table 3, the important increase (80–95%) of environmental load in the assembly phase can been seen for both desalination plants using EI 99 and Ecopoint methods. With the CML method, the increase is about 65–74%. In MED plant, the assembly stage has associated a higher environmental load than the operation phase of Ecopoints 97. Obviously, the higher relative load of the assembly phase is due to the significant reduction of primary energy consumption when waste heat is the driving force of the thermal desalination process. Also note the dramatic decrease of the global scores in the three applied methods when integrating thermal desalination entirely driven by waste heat, that is when integrated with other industrial processes.

Table 4: Relevant airborne emissions produced by MSF and MED when driven by waste heat

	MSF	MED
kg. CO_2 / m^3 desalted water	1.98	1.11
g. dust / m^3 desalted water	2.04	1.02
g. NO_x / m^3 desalted water	4.27	2.42
g. NMVOC / m^3 desalted water	1.22	0.59
g. SO_x / m^3 desalted water	14.79	16.12

4.1.2 LCA of desalination technologies versus different energy production models

Desalination is an energy intensive consumption process. This is confirmed from the results presented in previous sections. Moreover, thermodynamics establishes that the minimum theoretical work required for desalting seawater is about 0.8 kWh/m^3, depending on the salinity and seawater temperature [11]. This amount does not seem to be very important, but if the desalination capacity all over the world is taken into account (30 millions of m^3/day), which is continuously raising due to the increasing water scarcity, the final result is a non-negligible energy consumption. It is estimated that the primary energy consumed in all desalination plants of the world during 2002, producing about 0.2% of freshwater consumed, represented approximately 0.3% of fossil fuel energy consumed all over the world [31]. Note that fossil fuels represent nowadays about 80% of the primary energy consumed in the world [32]. In this context, it would be very interesting to analyze the potential of reduction of the environmental loads depending on the origin of the energy consumed by the different desalination technologies. Thus, the effect of moving towards different energy production models on the provoked environmental loads by desalination are analyzed in this section. In particular the effect of considering different patterns and policies of electricity production on the environment has been analyzed [16]:

- First, the European model is taken into consideration in order to analyze the impact of different desalination technologies in Europe (43% thermal, 40% nuclear, 17% hydropower), on average.
- Second, the Spanish model, in which different contributions are quite balanced (51% thermal, 35.5% nuclear, 13.5% hydropower) is considered.
- Third, the case in which an energy policy is adopted based mainly on fossil fuels is analyzed; in this case, the adopted model is the Portuguese electricity production model: 81% thermal, 3% nuclear, 16% hydropower.
- Fourth, the case in which a nuclear based electricity production policy is adopted is considered, which is the case of France: 11.5% thermal, 73% nuclear and 15.5% hydropower
- Finally, what would happen if renewable energies were used where the main source of energy is electricity is studied. In this case, the Norwegian model has been selected: 0.5% thermal, 0.5% nuclear and 99% hydropower.

Table 5: Environmental load corresponding to each life cycle phase and overall scores for MSF and MED entirely driven by waste heat. The calculus bases are about 379 hm^3 and 375 hm^3 of total water production for MSF and MED, respectively

Process	Life cycle phase	Unit	EI 99	Ecopoints 97	CML 2 *baseline*
MSF	Assembly	%	11.87	20.43	3.76
	Operation	%	88.13	79.56	96.24
	Final disposal	%	0	0	0
Total scores			39.3 MPoints	631 GPoints	0.0059
MED	Assembly	%	36.44	57.09	11.49
	Operation	%	63.56	42.91	88.51
	Final disposal	%	0	0	0
Total scores			25.9 MPoints	556 GPoints	0.0030

Table 6: Relevant airborne emissions produced by the analyzed desalination technologies (MSF and MED driven by waste heat) in different scenarios of electricity production

		kg. CO_2 / m^3 desalted water	g. dust / m^3 desalted water	g. NO_x / m^3 desalted water	g. NMVOC / m^3 desalted water	g. SO_x / m^3 desalted water
European model	MSF	1.98	2.04	4.27	1.22	14.79
	MED	1.11	1.02	2.42	0.59	16.11
	RO	1.78	2.07	3.87	1.10	10.68
Spanish model	MSF	2.37	3.08	5.32	1.11	16.87
	MED	1.31	1.54	2.93	0.54	17.14
	RO	2.18	3.10	4.88	0.99	12.73
French model	MSF	0.71	0.63	1.69	0.41	7.92
	MED	0.48	0.31	1.21	0.18	12.68
	RO	0.51	0.65	1.28	0.29	3.71
Portuguese model	MSF	3.27	3.21	7.76	4.09	27.52
	MED	1.76	1.61	4.16	2.02	22.70
	RO	3.08	3.26	7.32	3.97	23.81
Norwegian model	MSF	0.28	0.01	0.64	0.17	5.86
	MED	0.27	$6 \cdot 10^{-3}$	0.60	0.07	11.66
	RO	0.08	0.03	0.23	0.06	1.73

The most relevant emissions produced in the different scenarios for each technology are shown in **Table 6**. Note that for MSF and MED, it is considered that they are driven by waste heat coming from another industrial processes. If they were driven by fossil fuels, it is clear that, as shown in Table 2, this type of analysis would be meaningless for thermal desalination technologies.

Table 7 shows the results of this analysis. All the technologies have the same order of magnitude, and the MSF and MED processes, in general, have the highest and least environmental load, respectively. In some cases, the MED plant provokes a higher impact than the MSF plant, like in the predominantly renewable scenario with the EI 99 method and in the mainly nuclear and renewable scenarios with the Ecopoints 97 method.

In the three methods and technologies, the thermal and renewable situations are the highest and lowest impactant options, respectively, with a significant reduction of the environmental load when applying renewable energies.

From this analysis, it can be concluded that there is a very important potential of decreasing the environmental impact of desalination by only modifying the energy production model. It is noteworthy to comment on the French scenario: it has a high percentage of nuclear sources and the final accentuations for each system and method demonstrate a smaller environmental load than in the European or Spanish situations. We consider that this result is obtained because the nuclear wastes are not properly considered in the applied evaluation methods.

Table 7: Overall scores obtained by the analyzed desalination technologies with different scenarios of electricity production. The calculus bases are about 379 hm^3, 375 hm^3 and 383 hm^3 of total water production for MSF, MED and RO, respectively

		EI 99	Ecopoints 97	CML 2 *baseline*
		MPoints	GPoints	–
European model	MSF	39.3	631	0.00587
	MED	25.9	556	0.00301
	RO	33.9	500	0.00529
Spanish model	MSF	42.9	734	0.00874
	MED	27.7	607	0.00444
	RO	37.6	605	0.00818
French model	MSF	16.5	313	0.00247
	MED	14.7	398	0.00134
	RO	10.9	178	0.00185
Portuguese model	MSF	79.4	1,130	0.00947
	MED	45.6	804	0.00480
	RO	74.5	1,000	0.00894
Norwegian model	MSF	8.53	195	0.00084
	MED	10.7	340	0.00053
	RO	2.84	58.9	0.00020

5 Conclusions

In this work, a Life Cycle Analysis (LCA) has been applied for the most important commercial desalination technologies (MSF, MED and RO). The software SimaPro 5.0 has been used to conduct the analysis, which is structured as established phases by the standard ISO 14040 for LCA. Although the analysis is general and not very detailed, the results obtained are significant enough in order to obtain a general outlook concerning the less aggressive desalination technologies for the environment. Once the different systems had been represented and simulated, different evaluation methods have been applied (CML 2 *baseline* 2000, Ecopoints 97 and Eco-indicator 99), and the following conclusions have been reached:

- In all desalination technologies, and independently of the evaluation method used, the materials have little weight in the analysis, so the environmental load associated with the operation stage is much higher (88.6–99%) than that associated with assembly and final plant disposal (1-11.4%), due to the high energy consumption that desalination requires.
- For all evaluation methods applied, the RO plant has an associated environmental load which is significantly lower (one order of magnitude) than does the thermal desalting process (MSF and MED), because RO is more efficient and its energy consumption, in terms of primary energy, is about 5-6 times lower than thermal technologies [33].
- Comparing MSF and MED processes, the former is less efficient, since an energy viewpoint and MSF obtains more accentuation in the three applied methods. Although the energy consumption in thermal desalination technologies is very high, their environmental impact can be drastically reduced when they are integrated with other industrial processes in order to take advantage of the residual heat. This result is very important because it shows the high potential of decreasing the environmental impact associated with the thermal desalination technologies when properly integrated, since it offers an energy viewpoint, taking other production processes into consideration.
- Another important result is the high potential of decreasing or increasing the environmental impact of desalination depending on the energy production model or policy implemented in a region or a country. Thus, the scores and the airborne emissions obtained from an electricity production model based on renewable energies are about 65-70 times lower than those obtained when the electricity production model is mainly based on fossil fuels.

As a final conclusion of this first part, from the results obtained in this research work and with the present state of the art of the technology, it can be stated that desalination based on RO provokes a significantly lower environmental load than thermal desalination. This result is highly reinforced if the energy production model is oriented to renewable energies. However, thermal desalination technologies should not be refused because they present a great potential of environmental impact reduction when integrated with other production processes. Fortunately, desalination has a very important margin for minimizing its environmental load and the results presented in this paper indicate that a very interesting and promising field of research is available in order to achieve it.

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